Review and assessment of doctoral thesis "Test methods for the evaluation of radiation effects in high precision analogue and mixed-signal devices for space applications" by Ing. Jiří Hofman February 2019

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Synoptic review

This thesis reports on an ambitious project addressing several aspects of direct relevance to its title and covering a wide range of activities.

The context is low-cost commercial space missions – sometimes described, as here, in terms of a "New Space" paradigm – and their need to ensure reliably calibrated data acquisition systems (DAQ) in the space radiation environment, in particular when exposed to total ionizing dose (TID). Mr Hofman rightly points out that conventional radiation hardness assurance tests (RHA) focus on ensuring the reliable *function* of electronic systems – predicting a component or system operating lifetime as cumulative degradation due to radiation effects leads eventually to failure – rather than on *performance* during operation. Adequate performance is particularly important for the high-precision analogue and mixed-signal components typically found in DAQ systems used for scientific measurement. Mr Hofman emphasises astronomy in particular, although I observe that other aspects of spaceborne science, for example Earth observation and zero-gravity experiments, have similar requirements.

The first few chapters of the thesis provide background. Chapter 2 on space DAQ systems could usefully have been expanded, for example with graphical presentation of the treatment of measurement uncertainty, although appropriate references to standard manuals are given and are useful for readers who might lack the relevant background. (Many workers in radiation effects, many electronic engineers generally, do struggle with these concepts although I think this is not the case with Mr Hofman, who shows good understanding of measurement science.) This chapter also explains the current interest in commercial off-the-shelf technologies (COTS) for space applications.

Chapter 3 is a significant chapter, describing the effects on electronic components of space radiation on the one hand, and temperature on the other. The emphasis is on semiconductor

components in the major technological families of interest; bulk CMOS and bipolar electronics in silicon. This is standard background material, but it is thorough, well presented, and evidently well understood. The issue of synergy between TID and temperature effects is an important aspect of this work; so far as I am aware very little work has been published on this synergy. This chapter identifies the challenge caused by the confounding effect of temperature variations on the evaluation of TID effects; something that will be addressed later in the thesis as part of the original work.

Chapter 4 reviews conventional RHA techniques, as embodied in standard procedures specified by military and space agencies, and reviews the published literature on TID tests on two devices of particular interest for spaceborne DAQ: voltage references and analogue-digital converters (ADCs). Gaps are identified.

Chapter 5 introduces concepts for radiation testing for the New Space era. The paradigmatic New Space project – low-cost launch of a lightweight spacecraft with COTS electronic components – is the "cubesat" nanosatellite concept. New Space demands low-cost radiation testing with short lead time; and in-situ testing is identified as potentially meeting these needs, largely because of opportunities for automation including the ability to undertake more complex tests, typified by board-level tests or combined TID/temperature coefficient testing. A complementary test approach – on orbit testing of technology demonstration flight experiments, for example using the cubesat platform itself – is also described. Both in-situ ground tests and on-orbit testing are considered later in the thesis, as part of the original work submitted.

Original work begins in chapter 6, which described development and characterisation of experimental equipment and methods. Much work has gone into this part of the project, which demanded skills and knowledge of ionizing radiation generation and dosimetry, electronic instrumentation and control, electronic hardware development and a range of programming techniques, from microcontrollers to automatic test equipment. The work described in this chapter demonstrates Mr Hofman's ability to apply appropriate techniques in design and evaluation of instrumentation systems for a wide range of applications. He is skilled at that.

Chapters 7 to 9 report on TID experiments on three COTS component types: PMOS transistors (for use as dosimeters), voltage references, and ADCs. This work informs that of chapter 10, which describes development of spaceborne radiation test systems, "RADEX", for deployment on a cubesat platform. Somewhat confusingly, the RADEX work is described as being "in-orbit experiments" although the experimental work presented in chapter 10 is ground-based qualification of development models of the RADEX system. Nonetheless, the work presented there is valuable and the lack of flight data is a natural consequence of the lead times programme risks inherent in space programmes, also in the New Space era.

In chapter 7, comparison is made between the behaviour of RADFETs (p-channel MOSFET transistors optimized for use as dosimeters) from the two suppliers of these devices. Standard commercial PMOS transistors were also considered as alternatives for this application. TID response was investigated, with particular interest in the influence of TID on temperature coefficient of the RADFET measurand (gate-source threshold voltage, V_T). The challenges posed by the confounding effect of TID on temperature calibration were noted and suggestions made for addressing this. A choice of RADFET for the RADEX payload was made and justified; the standard MOSFET was also recommended as a complementary dosimeter, although its radiation response was found, understandably, to be less well controlled than in the optimized designs. Results from the use of this non-standard device as an in-flight dosimeter will be very interesting. These experiments were the first to use the in-situ test system whose development

was described in Chapter 6. This work was published in international conference and journal papers, describing both methodology and experimental results.

Voltage references are key components of DAQ systems, and in chapter 8 the effect of TID on their performance was considered, including the effect on temperature coefficient of reference voltage. Evaluation of error sources in the output voltage were made. This appears to be the first work to have published results of this kind. Results from these experiments were presented at international conferences.

In chapter 9, TID experiments on ADCs are described. In-situ measurements were used to perform dynamic system tests with fine resolution in dose. The measurement methodology was successfully proven, but firm conclusions on device performance were, rightly, not drawn because of the very limited number of samples available for test.

Chapter 10 describes the RADEX experiment. The aim was to develop an environmental monitor and technology demonstration or qualification platform for future deployment on a nanosatellite. The design of the RADEX system is described as are tests of development models, including TID tests. Testing encompassed several components on the system, including current sources and temperature sensors as well as the components tested separately in earlier chapters and selected for inclusion in RADEX.

Chapter 11 concludes the main body of the thesis. It provides a review of the content and recaps the contribution of the thesis, with very many suggestions for future work.

Assessment

The topicality of Mr Hofman's work is clear. Its context is the New Space paradigm for commercial and scientific exploitation of space with reduced cost of access. This is an exciting field of engineering endeavour and will be for the foreseeable future. This work is timely and relevant. (I am finalising my review on the day when, sadly, the first privately funded moon mission has failed on landing but, more happily, the first commercial launch of Space X Falcon Heavy appears to have been a success.)

One of the challenges for New Space is in qualifying COTS electronic components for space (COTS being preferred over radiation-hardened components for their availability, performance and price), and doing so quickly and cheaply enough to meet the demands of the new paradigm. Mr Hofman understands and explains this well, and makes progress towards meeting this challenge.

The thesis is set well in the context of the state of the art. The extensive set of references is pertinent and up to date. Mr Hofman understands and exploits his references well; for example, in applying the experience of workers at CERN to his very different application.

Mr Hofman's work is pertinent and original. His principal contribution is in developing total ionizing dose test methods for components for space application, especially high-precision analogue components, and especially for measurement calibration. (I note with pleasure that this is reflected accurately in the thesis title.) One application of particular interest is evaluation of the effects of total ionizing dose on temperature coefficient of gate-source threshold voltage in RADFET dosimeters (V_T is used as a measure of received dose); this aspect of the work has led to recommendations for improved calibration procedures for in-flight calibration of RADFETs.

This work has led to several conference papers, presented at the major international conferences in the field of ionizing radiation effects in electronics, and two journal papers, in IEEE Transactions on Nuclear Science, the main international journal in this field. This demonstrates well deserved peer recognition of the quality of Mr Hofman's work. He has demonstrated specialist expertise in his field.

The thesis is well presented with very few production errors which do not materially affect its quality. It is rather long, and would have benefited from greater conciseness, with more data reduction, fewer chapters, and mini-summaries at the end of each chapter. (Where these summaries were present, notably in chapters 7 to 10, they were useful, especially as the quantity of data presented was so great.) There were also too many TLAs. But I think the style and content reflect the ambitious scope of the project and the enthusiasm and commitment of the author, and my criticisms here are relatively minor.

Summary

I have no doubt that the thesis meets the standard generally required for the award of the degree of Doctor of Philosophy.

I have no doubt that the work is Mr Hofman's own. He has made an original contribution to knowledge. He has demonstrated a high level of competence as an engineer and as a research scientist, exploiting a range of skills to bring his project to successful fruition. He has shown that he can make informed judgements on complex issues in an advanced field of study. He has communicated his work well, including presentations at international conferences and publication in the leading international journal in his field.

It might be useful for me to compare Mr Hofman's work with equivalent work undertaken at British universities. Our system of research degree examinations in Britain is such that students may be asked to revise their theses following a viva-voce examination. It is normal for some corrections to be required; in my experience as an examiner and as a supervisor of PhD projects, most PhD theses require substantial revisions following examination. So I naturally look for things to correct. I am confident that Mr Hofman would not be asked to revise his thesis, were he to have conducted his work for examination at a British university, its deficiencies being few and minor, and I have no doubt that he would be awarded the degree of PhD, having clearly demonstrated that he has met the requirements to do so.

This is one of the better theses I have examined and I recommend that Mr Hofman should be awarded the degree of Doctor of Philosophy on the basis of a very good piece of work.

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